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EXPERIMENTAL INVESTIGATION OF THE INTERACTION OF OVERTAKING SHOCK WAVES IN AIR

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U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

EXPERIMENTAL INVESTIGATION OF THE INTERACTION OF OVERTAKING SHOCK WAVES IN AIR

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ABSTRACT: An exploratory experimental program has been completed to determine in a rough though quantitative way the nature of the multiple charge effect on air blast.

It does not appear that a blast pulse of long duration, without multiple peaks, can be made by using multiple charges of high explosives. When multiple charges were fired in air, the positive duration of the combined shock wave in the range measured, was never appreciably larger than the positive duration of the individual shock wave having the longest duration.

The duration of the individual shock was taken as the value it would have in undisturbed air; in fact, the positive duration from multiple charges was even less than for a single charge in a great many of the experimental conditions probably because the negative phase from one charge cut off the positive phase of the other.

The fact that the positive duration was not increased was previously noted in the far Mach region where the shocks from a charge and its image were combined.

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The question of how the pressures of several shock waves in air combine and the question of pressure enhancement has not been answered completely but light has been shed on some of the important parameters affecting the problem.

It has been found, for example, that when one shock wave overtakes another, the wave which overtakes the leading wave is attenuated by anywhere from 0 to 70 per cent. This attenuation is greater for weak shocks, 2-4 psi, than for strong shocks, 30-50 psi; furthermore, the further the trailing shock progresses toward the front of the leading shock the greater is the attenuation of the trailing one.

Pressure enhancement over a unit charge was not achieved at any time after the shock waves combined nor was there any indication that pressure enhancement was possible. No increase in positive impulse has been found in these experiments over what would be obtained by a single charge located at the nearer distance.

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The work described in this paper has been done first to find out if the blast wave may be enhanced as a result of using multiple charges instead of a single charge with the same total weight, second to provide some basic experimental data that may be useful in studying the interaction of shock waves, and third, to find out if multiple shock phenomena could be used in some way to produce a long duration shock. This work was done under Project NOL Re2c-2-1.

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By direction

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ILLUSTRATIONS

EXPERIMENTAL INVESTIGATION OF THE INTERACTION OF OVERTAKING SHOCK WAVES IN AIR

INTRODUCTION

1. In an explosion a large quantity of heat and light is liberated, gases are produced at a high temperature and pressure, and a pressure wave known as a shock wave is sent out into the surrounding medium from the center of the detonation. The reason for the development of the shock wave which is essentially a discontinuity of pressure and particle velocity, can be readily seen by considering the detonation product gases as a spherical piston pushing outward the surrounding medium with a velocity u, the velocity of the spherical gas piston, and at any time the disturbance is communicated to the surrounding air with a velocity of sound c relative to the air, and a velocity relative to the ground of c + u. Now as time increases the piston continues to expand rapidly increasing the temperature and density of the air immediately surrounding the piston which increases the local sound velocity resulting in an increase in the speed of propagation of the disturbance. Thus, as the detonation product gases expand the local speed of sound increases, increasing the speed of propagation of the disturbance into the surrounding medium. This process results in a pressure front building up and becoming steeper as the later and faster disturbances traveling through the heated air catch up to the earlier and slower ones until limited by the viscosity and heat conductivity of the medium. At this time the shock front is formed.

2. In addition to a pressure discontinuity, a shock front is accompanied by an elevated temperature and by motion of the air which, together with the velocity of the shock, are related to the shock pressure. The equations governing the various parameters at the shock front were formulated by Rankine and Hugoniot by the application of the laws of conservation of mass, momentum and energy across the shock front.

3. The pressure in the shock wave is a function of the distance from the charge and, at a fixed distance, is a function of time. At fixed distances from the explosion the pressure in the shock front rises to its peak value in a time which is effectively instantaneous, decays gradually

with time until it reaches a minimum (which is below atmospheric pressure), and then returns slowly to preshock atmospheric pressure. This decay of pressure with time is interrupted by a secondary shock occurring normally when the pressure has decayed nearly to atmospheric pressure.

4. The maximum value of the pressure in the shock wave in excess of atmospheric pressure is called the peak pressure (P_s) and the time required to decay to atmospheric pressure will be termed the positive duration. Positive duration is measured by extrapolating the pressure-time curve to 0 pressure as if the secondary shock were not there. Referring to fig. 2 which shows a number of sample records, the area bounded by the positive part of the pressure curve and the axis of atmospheric pressure,

$\int_0^T P(t)dt$, is called the positive impulse. The interaction of overtaking shocks will be discussed in terms of the three above-mentioned parameters, peak pressure, P_s, positive duration, τ, and positive impulse, I.

5. Investigations in the field of overtaking shocks have to the best of this author's knowledge, not been made to date, probably because of the difficulty of analyzing the non-linear behavior of the resultant interaction. Nevertheless, there has been much speculation on this subject. It is hoped that this paper will help provide some fundamental experimental data to be used as a basis for further study.

6. The specific question this work will answer is if two shock waves coming from separate sources are arranged in some way to be superimposed, how will the parameters of peak pressure, positive duration and positive impulse be affected. In other words, how do shock waves add up and what parameters affect this process.

7. As discussed, disturbances are propagated faster relative to the ground in a medium having a high local speed of sound, that is in a medium of high temperature and pressure, than they would in a medium of a lower local speed of sound. Thus a shock wave in general will catch up to another shock wave even if the velocity of the trailing shock relative to the sound velocity in the medium in which it is traveling is less than the relative velocity of the leading shock front. In other words, a shock of less

strength can overtake one of greater strength simply because the value of c in the medium behind the latter is so greatly increased by the passage of the shock.

EXPERIMENTAL PROCEDURE

8. The shock wave produced in air by a one pound spherical pentolite charge has been well established by a number of investigators (reference (b)) so that the multiple shocks produced by two charges can be easily identified and the data can be analyzed in terms of known shock wave parameters. By this it is meant that the identity of a shock wave that has not been affected by another shock can be correlated with the charge it came from by measuring its parameters.

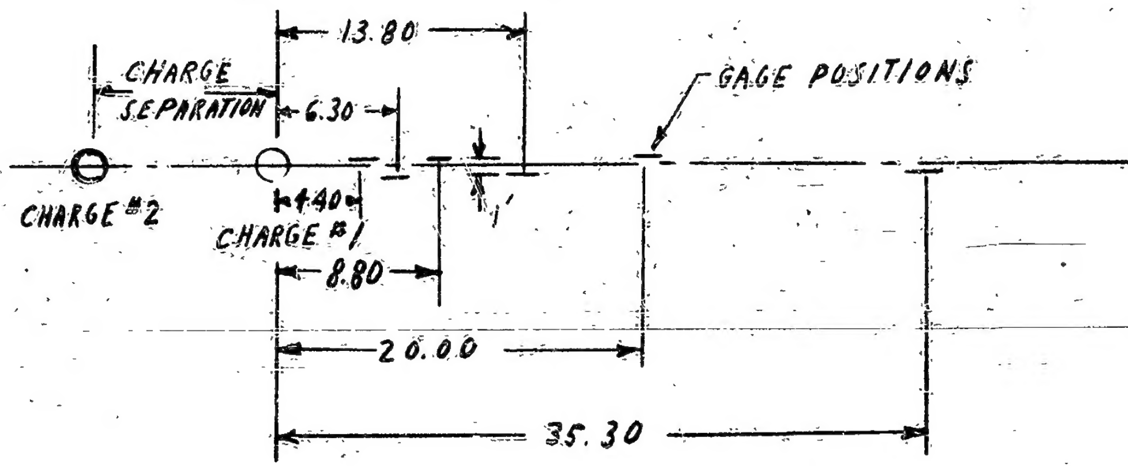

Fig. 1 - Plan of Experimental Set Up

9. To measure the shock waves emanating from two charges six tourmaline piezo-electric gages were placed at six distances in a line with the two charges as shown in Fig. 1. Gages and charges were located in a horizontal plane 12 ft above the ground to delay ground reflections until the entire positive phase of the incident shock was recorded.

10. The signals from the gages were led back to the record-

ing equipment by 250 ft of cable and were then amplified and impressed on the deflection plates of a cathode ray tube. The resulting deflection of the cathode ray spot was recorded on 35 mm film as a function of time by a rotating drum camera. Conventional techniques of piezoelectric pressure measurements were used, reference (c). Rectangular baffles having a length twenty-four times the thickness surrounded the gages to minimize the difficulty occurring as a result of flow which causes the pressure on the gage to be somewhat less than the free field pressure.

11. Charge #2 was fired first, then charge #1 after a known delay. The time delay for firing was recorded as short duration pips on the same film trace as the pressure-time curves by utilizing the surge current going into the electric detonators to generate a voltage for this recording, Fig. 2.

12. The method used to carry on this investigation was to fix a charge separation of 0, 1, 2, and 3 ft and fire the two charges at time differences from 0 on up until the two shocks no longer were reacting in any way with each other. This program was exploratory in nature; only two shots of each experimental condition were made.

13. Measurements were made of pressure, positive impulse and positive duration of shock waves that were caught up and of those that were in the process of overtaking each other. In order to fire charges at 0 separation and at different times the charges were placed 2 ft apart at right angles to the gage line. Each charge was then at approximately the same radial distance from each of the gages, giving the desired effect of zero charge separation.

14. Single one pound charges were fired and the parameters of peak pressure, positive impulse and positive duration were read and compared with the accepted values to establish the validity of the gage calibration and recording systems.

15. Two one pound charges were tied together and fired as a single charge. The results of these firings were compared to the two pound blast data as determined from the scaling laws and the one pound accepted experimental values. Some discrepancy is to be expected because of charge shape not being spherical.

16. All charges used in the series of experiments described in this report were 470 grams of cast spherical 50/50 pentolite centrally initiated with an engineer special electric detonator.

17. The effect of gage size on peak pressure was neglected. This amounts on the average to a 5 per cent error making the peak pressure read low. The effect of the charges being 3 per cent heavier than one pound on the average was also neglected. This tended to compensate for the effect of neglecting gage size errors. Since only two shots were fired in any one situation errors caused by neglecting these factors were small compared to the normal scatter in this kind of work.

18. Tables I through IV are tabulations of the experimental data in these series of experiments and are self-explanatory.

ANALYSIS OF DATA

19. Figure 3 shows graphs of the percentage of the trailing shock's normal peak pressure value that resulted when it propagates into the positive phase of the leading shock. By normal peak pressure value is meant the value it would have in undisturbed air. This percentage is plotted as a function of the ambient pressure in the leading shock at the instant of arrival of the trailing shock front and also as a function of this ambient pressure expressed as a percentage of the peak pressure in the leading shock. From the graphs it can be seen that in general the loss of peak pressure in the trailing shock increases as the trailing shock enters a higher pressure region. At the 8.80, 13.80, 20.00 and 35.30 ft gage positions when the shocks are completely caught up the reduction in the normal free air peak pressure in the trailing shock averages 61 per cent with a range of 58 to 65 per cent. Thus the final pressure loss figure of the trailing shock is not very dependent on the pressure level of the leading shock or the trailing shock. The numbers next to points on the graphs, Fig. 3, represent the distance in feet between the charges when fired. The larger this distance the greater the difference in pressure of the two shocks. The method used to determine this peak pressure loss is as follows. The leading shock's pressure is determined from known pressure-distance data thus establishing a pressure scale (psi per inch of deflection) for the pressure-time record; using this pressure scale the pressure in the trailing shock is determined, Fig. 3. This pressure is then compared with the pressure this shock would have had had it not interacted with the leading shock. The pressure the trailing shock would normally have had was taken from known pressure-distance data for these charges, reference (a). Thus it can be seen that the percentage loss in pressure has been derived without the aid of the calibration constant of a tourmaline pressure gage.

20. When a single charge of twice the weight of one of these charges is fired, the pressure can be predicted from the scaling law which states:

$$P_s = f\left(\frac{R}{W^{1/3}}\right)$$

where P_s equals the peak pressure
f is some function of pressure
R is radial distance from charge
W is the weight of the charge.

A form of this equation that fits experimental pressure-distance curves reasonably well is as follows:

$$P_s = A\lambda^{-n}$$

λ is reduced distance $\frac{R}{W^{1/3}}$

A is a constant

n is the slope $\frac{dP}{d\lambda}$.

Thus if we wish to know how much larger the pressure is from a larger charge of W_2 lbs compared to a smaller charge of W_1 lbs, we write the following ratio down:

$$\frac{P_2 = A\lambda_2^{-n}}{P_1 = A\lambda_1^{-n}} = \left(\frac{\lambda_2}{\lambda_1}\right)^{-n} = \left[\frac{\frac{R_2}{W_2'^{1/3}}}{\frac{R_1}{W_1'^{1/3}}}\right]^{-n}$$

make $R_1 = R_2 = R$ and adjust W_1' and W_2' such that the value of λ_1 and λ_2 remain unchanged.

Solve for $$\left.\frac{P_2}{P_1}\right|_R = \left(\frac{W_2}{W_1}\right)^{\frac{n}{3}} \qquad (1)$$

and drop primes.

Equation (1) is an expression for relative pressure at a given distance for two different weights of explosive.

21. The table below gives the ratio of pressure one obtains from two pounds of charge relative to a one pound charge as a function of distance.

22. These values were calculated using equation (1) and a value of n as measured from the accepted pressure-distance curves. If we imagine this relative pressure ratio to consist of the pressure from two one-pound charges and one of these charges contributed its normal free-air pressure, as is the case for the leading shock, and the other contributed a fraction of its normal pressure, as the trailing shock, we find that the fraction of the relative pressure ratio above one is analogous to the fraction of the normal free-air peak pressure of a trailing shock added to a leading shock after catch up. Experimental values for overtaking shocks are tabulated in accordance with the analogy as described.

23. The experimental data in the table below were obtained by considering the fraction of the trailing shock's undisturbed peak pressure value added on to the leading shock. Thus for multiple shocks to combine in such a way as to increase the peak pressure over a unit charge of equivalent weight, the trailing shock would have to add more than say 56 per cent of its free air value to the leading shock at the 8.80 ft distance.

R feet	Equation (1) $\frac{P_2}{P_1} = (2)^{\frac{n}{3}}$	Experimental Data 1 + fraction of trailing shock's normal peak pressure added to leading shock
4.40	1.72	
6.30	1.65	
8.80	1.56	1.42
13.80	1.46	1.40
20.00	1.38	1.35
35.30	1.32	1.40

Looking at the above table one sees that by combining shocks from two 1-pound charges fired separately, no real difference in final shock wave pressure is obtained than if a single 2-pound charge were fired.

24. Thus from this data, charges fired separately cannot enhance the blast wave over a single charge of the same collective weight; and in fact the blast is reduced if analyzed on the basis that the charge distance was that from the nearest charge. This is borne out in the pressure-distance graph, Fig. 4 for a 2-pound charge and for the various multiple charge shots studied after catch up.

25. The positive duration of all the fully combined shocks showed one interesting property. The positive duration of the combined shocks is no larger than the largest positive duration in undisturbed air of either of the two shock waves, up to distances of 16 ft from the nearest charge. Beyond 16 ft positive duration seems to increase and at 35 ft it looks similar to what would be produced by 2 pounds of charge. See Fig. 5 in which positive duration of combined shocks is plotted against distance from the further charge.

26. The duration of shocks initially in the far Mach region exhibits this same behavior. That is, although two nearly equal shocks have combined (charge and image charge), the incident and reflected, duration of the combination appears no larger than that for one of the shocks. There is the tendency for the duration of the Mach shock at large distances to look like that of a shock produced by twice the weight of charge. This duration effect was observed in the film records from reference (d). The reason for the delay in increasing the duration over the single charge duration is probably because the shock front velocity is increased only after the shocks have caught up. The point in space where the pressure in the shock has decayed to atmospheric, travels with the speed of sound and the shock front needs time to make its slightly greater velocity account for an increase in positive duration, whereas in a single charge of twice the weight the initially faster shock velocity has more time to get ahead of the cross-over point resulting in a wave of longer duration.

27. Since the duration of the shocks from multiple charges shows no enhancement over that of the shock from a single charge and since the peak pressure of the multiple shocks shows no enhancement over the shock from a single charge then it is quite reasonable to expect that the impulse, $\int P(t)dt$, will show no enhancement barring any change in rate

of the pressure decay with time. As can be seen in Fig. 6, this is borne out by the data. The two 1-pound charges fired at separated points produced impulses after catch up that were less than if the two 1-pound charges were fired together at the nearer distance. Furthermore the larger the charge separation the less was the positive impulse of the combined shocks, which is what could reasonably be expected.

28. It is to be noted that the conclusions arrived at in this report hold only for overtaking shock waves. These results should not be applied to colliding shocks.

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b. Free Air Blast Measurements on Spherical Pentolite by W. E. Curtiss, Ballistic Research Laboratories, Report 544; July 1951, Restricted.

c. Apparatus for the Measurement of Air Blast Pressures by Means of Piezo-electric Gauges by G. K. Fraenkel, March 1946, NDRC Report No. A-373, OSRD Report No. 6251 (Unclassified).

d. Experimental Shock Wave Reflection Studies with Several Different Reflecting Surfaces by E. M. Fisher, Sep 1951, NAVORD Report 2123 - Confidential.

TABLE I

Peak Pressure (psi) of Combined Shocks (Charges 0' apart)*

Distance ft / Shot #	4.40	8.80	13.80	35.30	Firing Time Delay MS
51	72.11	17.96	7.83	1.88	1.61
55				1.60	3.91
56				1.48	
57				1.65	
58	60.38	17.50	7.11	1.51	1.0
Average	66.25	17.73	7.47	1.62	

*Each charge is the same distance from gages but separated 2' apart at right angles to gage line in order to fire the two charges at separate times.

Peak Pressure (psi) of Combined Shocks (Charges 1' apart)

Distance ft / Shot #	4.40	6.30	8.80	13.80	35.30	Firing Time Delay MS
5				7.65	1.37	*
6				7.10	1.73	*
7				7.10	1.49	*
8	51.29	24.94	13.06	6.68	1.41	*
9	54.61	22.02	13.76	6.38	1.40	*
10	64.91	29.19	13.25	6.54	1.46	*
11	39.15	18.06	9.73	7.09	1.48	*
13					1.50	0.69
14					1.55	0.74
Average	52.49	23.55	12.45	6.93	1.49	

*Not measured.

TABLE I

Peak Pressure (psi) of Combined Shocks (Charges 2' apart)

Distance ft / Shot #	4.40	6.30	8.80	13.80	35.30	Firing Time Delay MS
15					1.33	1.06
16	46.07	24.45	11.66	5.69	1.35	1.10
17	56.10	23.46	12.12	5.99	1.36	1.13
18	61.28	29.71	14.69	7.06	1.63	1.84
21				6.81	1.53	3.66
22				7.16	1.48	3.65
23					1.70	2.94
24					1.50	2.84
25		22.72	13.53	6.59	1.57	2.16
26					1.59	3.99
29	45.14	17.47	11.91	6.74	1.46	1.13
Average	52.14	23.56	12.78	6.58	1.50	

Peak Pressure (psi) of Combined Shocks (Charges 3' apart)

Distance ft / Shot #	4.40	8.80	13.80	35.30	Firing Time Delay MS
30				1.27	1.14
31				1.26	1.04
36				1.38	0.75
37				1.47	0.66
39				1.39	1.00
40				1.35	1.02
41	49.14	11.32	5.65	1.55	1.30
42				1.59	1.32
43	45.72	11.60	5.77	1.33	1.64
44		12.35	5.91	1.33	2.32
45		13.95	6.98	1.48	
46		14.66	8.30	1.51	3.88
47			7.37	1.56	4.02
48				1.56	4.58
50				1.57	5.18
Average	47.43	12.78	6.66	1.44	

TABLE II

Positive Impulse (psi-ms) Combined Shocks (Charges 0' apart)*

Distance ft / Shot #	4.40	8.80	13.80	35.30	Firing Time Delay MS
51	19.68	13.08	7.07	3.13	1.61
55				2.66	3.91
56				2.70	
57				2.62	
58		9.93	6.82	2.50	1.0
Average	19.68	11.50	7.44	2.72	

*Each charge is same distance from gages but separated by 2' in a direction at right angles to gage line in order to fire the two charges at separate times.

Positive Impulse (psi-ms) Combined Shocks (Charges 1' apart)

Distance ft / Shot #	4.40	6.30	8.80	13.80	35.30
5				6.38	2.23
6				7.31	2.82
7				7.19	2.51
8	16.96	12.02	8.34	6.39	2.33
9	16.60	11.50	9.13	6.35	2.15
10	17.22	12.24	8.90	6.27	2.48
11	14.78		10.00	6.74	2.02
Average	16.39	11.92	9.09	6.66	2.36

TABLE II

Positive Impulse (psi-ms) Combined Shocks (Charges 2' apart)

Distance ft / Shot #	4.40	6.30	8.80	13.80	35.30	Firing Time Delay MS
15					2.42	1.06
16	13.17		7.90	5.55	2.13	1.10
17	11.72	10.43	7.64	5.93		1.13
18	16.07	11.72	9.95	6.78		1.84
21						
22				7.06	2.88	3.65
23					2.94	2.94
24					2.44	2.84
25		9.80	8.96	6.69	2.74	2.16
26					2.72	3.99
29	13.02	10.68	9.04	6.56	2.41	1.13
Average	13.50	10.66	8.70	6.43	2.58	

Positive Impulse (psi-ms) Combined Shocks (Charges 3' apart)

Distance ft / Shot #	4.40	8.80	13.80	35.30	Firing Time Delay MS
37				2.45	0.66
39				2.33	1.00
41	14.15	8.08	5.32	2.77	1.30
42				2.54	1.32
43	13.32	8.66	5.41	2.54	1.64
44	17.35	8.46	5.83	2.22	2.32
45		7.88	6.58	2.45	
46		10.02	7.49	2.44	3.88
47			6.72	2.36	4.02
48				2.42	4.58
50				2.50	5.18
Average	14.94	8.62	6.22	2.45	

TABLE III

Mean Experimental Values of Positive Duration (τ), ms, vs Distance from Further Charge for Combined Shocks

Distance ft	τ
5.40	1.11
6.40	1.08
7.30	1.44
7.40	1.22
8.30	1.45
9.30	1.46**
9.80	1.85
10.30	1.88
11.80	2.09
14.80	2.50
15.80	3.06
16.80	2.60
21.00	3.01
23.00	3.19*
36.3	3.74
37.3	4.05
38.3	4.25

Typical Examples of Scatter in Mean Values Listed in Main Table

	*	**
	3.18	1.36
	3.21	1.41
	3.04	1.56
	3.32	1.51
	3.35	
	3.05	
Mean	3.19	1.46

TABLE IV

BLAST DATA FOR CONTROL SHOTS

Experimental Peak Pressures (psi) for 1 and 2 pounds of Pentolite

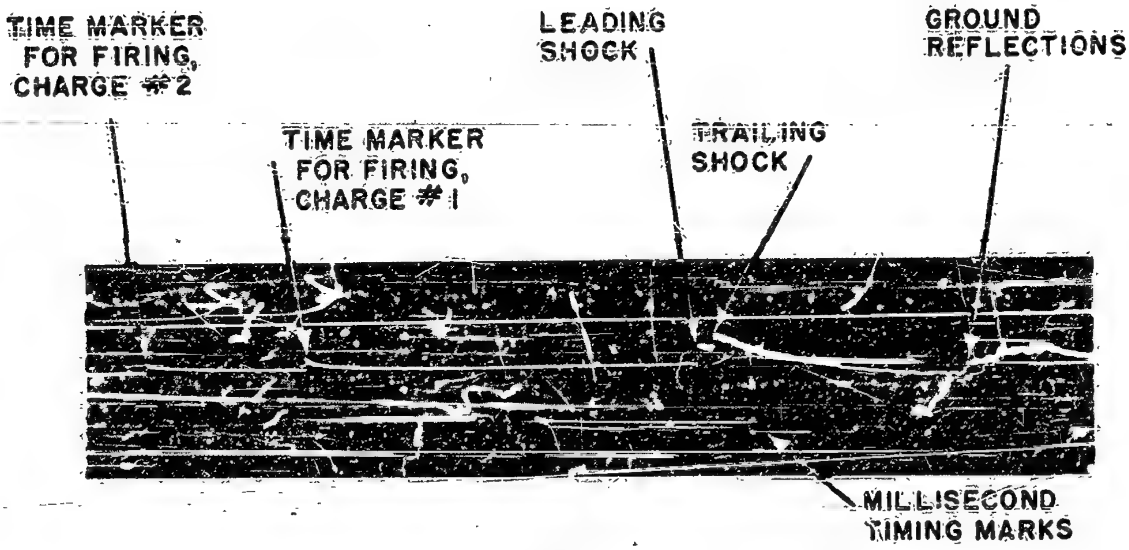
Distance ft / Shot #	4.40	6.30	8.80	13.80	35.30
1 lb (1	50.95		9.13	4.96	1.14
1 lb (2	48.54	20.84	9.94	4.91	1.12
Average	49.74	20.84	9.54	4.94	1.13
2 lb (3	49.98		12.75	6.95	1.68
2 lb (4	50.50	23.28	13.57	6.02	1.74
Average	50.50	23.28	13.16	6.49	1.71

Experimental Positive Impulses (psi-ms) for 1 and 2 pounds of Pentolite

Distance ft / Shot #	4.40	6.30	8.80	13.80	35.30
1 lb (1	10.71		6.34	4.54	1.60
1 lb (2	11.84	9.27	6.59	4.60	1.62
Average	11.28	9.27	6.46	4.57	1.61
2 lb (3	16.37		11.02	8.00	2.88
2 lb (4		13.42	11.75	8.20	2.66
Average	16.37	13.42	11.38	8.10	2.77

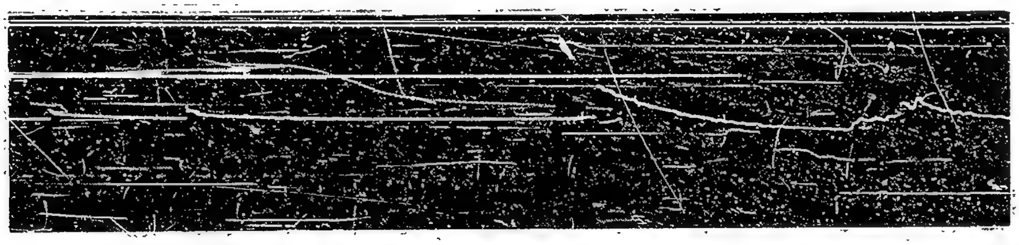
POSITIVE DURATION (MS) CONTROL SHOTS

Distance ft / Shot #	4.40	6.30	8.80	13.80	20.0	35.3
1 lb (1	0.86		1.86	2.27	2.50	3.40
1 lb (2	0.84	1.35	1.75	2.26	2.68	3.45
Average	0.85	1.35	1.81	2.27	2.59	3.43
2 lb (3	1.25		2.27	2.81	3.14	3.94
2 lb (4	1.07	1.37	2.34	2.81	2.92	3.54
Average	1.16	1.37	2.31	2.81	3.03	3.74



SHOCK WAVES IN OVERTAKING PROCESS

CHARGE SEPARATION 3 FEET
FIRING TIME DIFFERENCE 4.52 MS
CHARGE #1 TO GAGE DISTANCE 20.00 FEET



TWO SHOCK WAVES COMBINED

CHARGE SEPARATION 3 FEET
FIRING TIME DIFFERENCE 4.02 MS
CHARGE #1 TO GAGE DISTANCE 20.00 FEET

FIG. 2
TYPICAL RECORDS

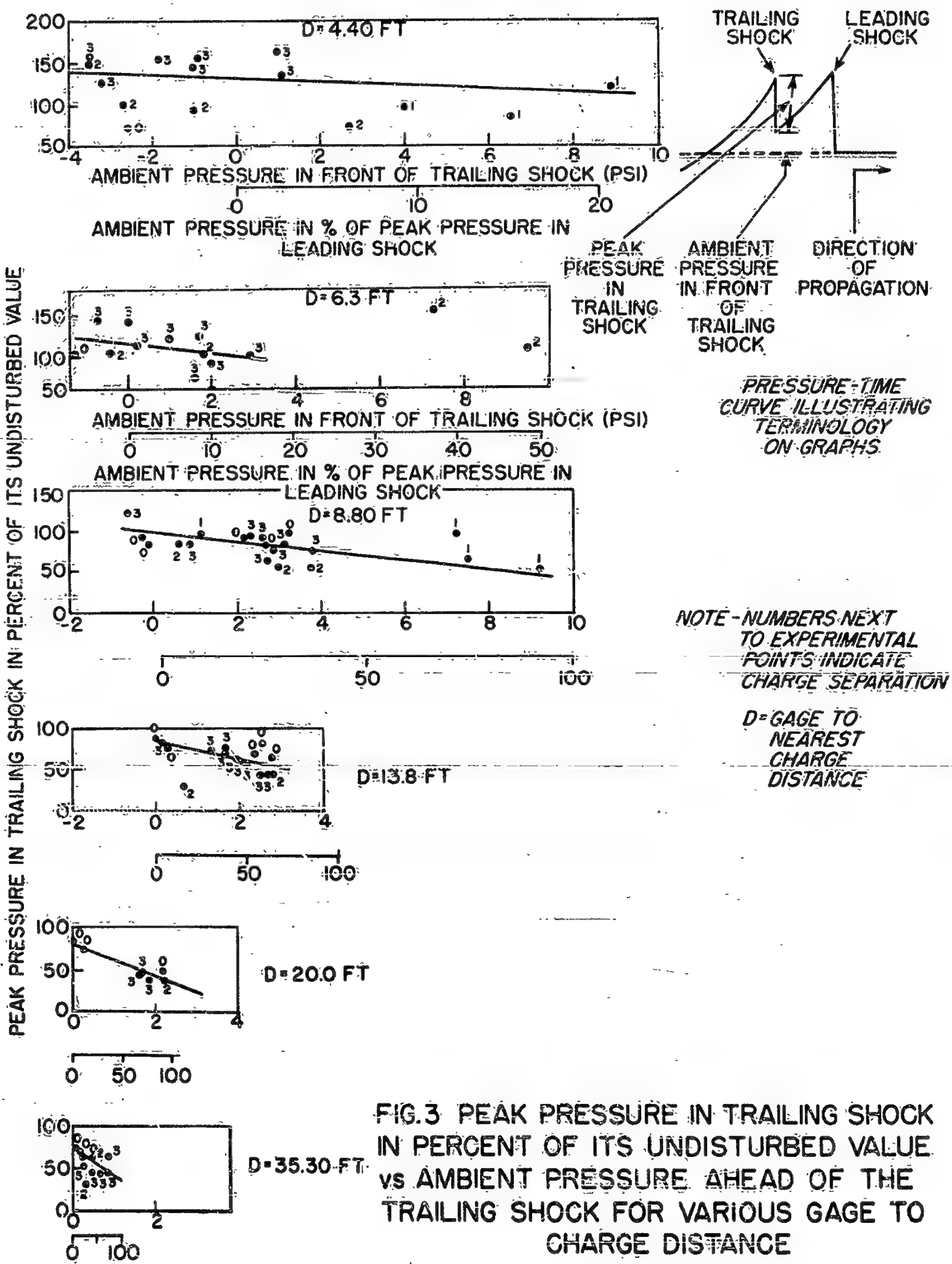


FIG. 3 PEAK PRESSURE IN TRAILING SHOCK IN PERCENT OF ITS UNDISTURBED VALUE vs AMBIENT PRESSURE AHEAD OF THE TRAILING SHOCK FOR VARIOUS GAGE TO CHARGE DISTANCE

FIG. 4 PEAK PRESSURE VS DISTANCE FROM NEAREST CHARGE

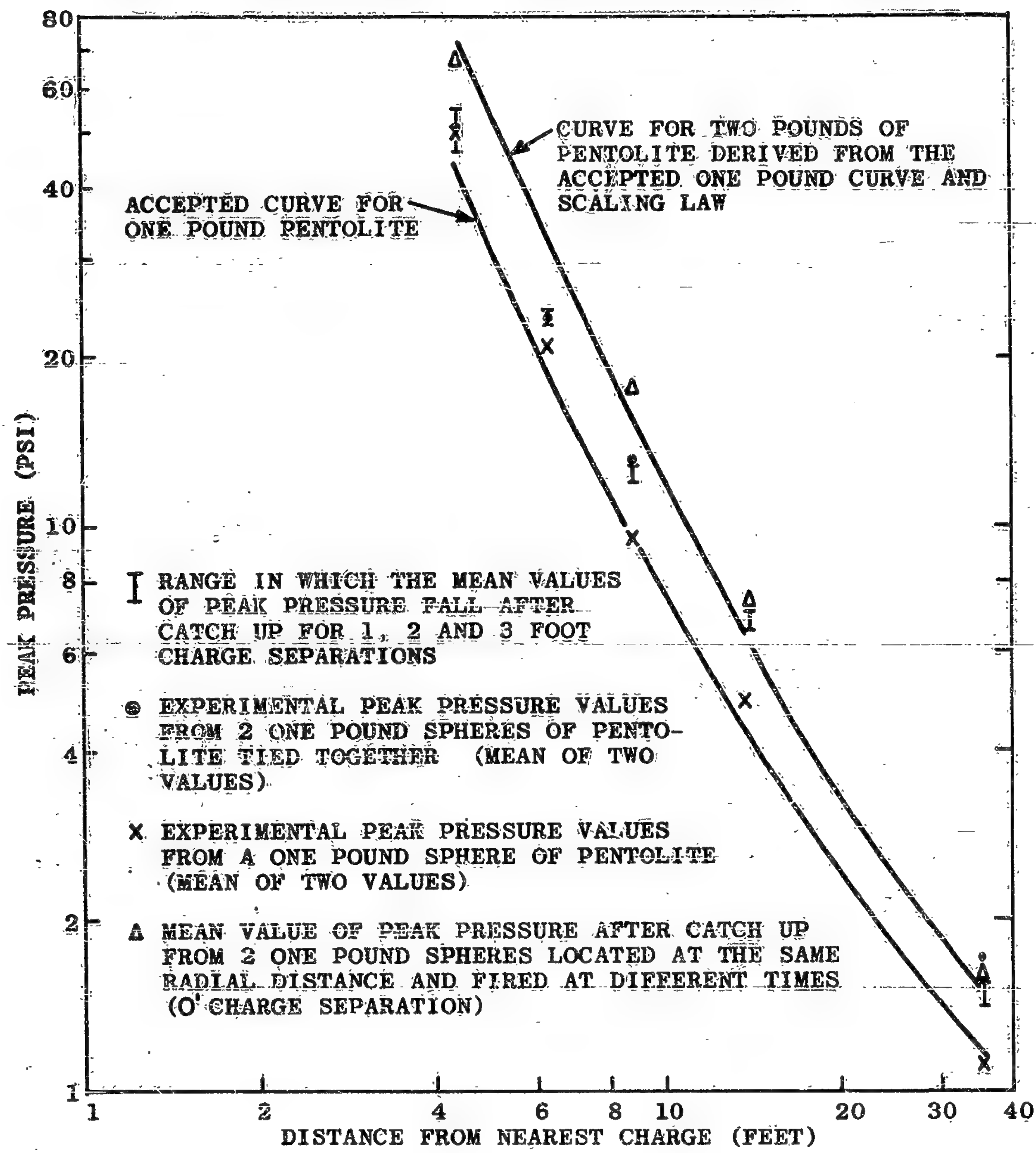
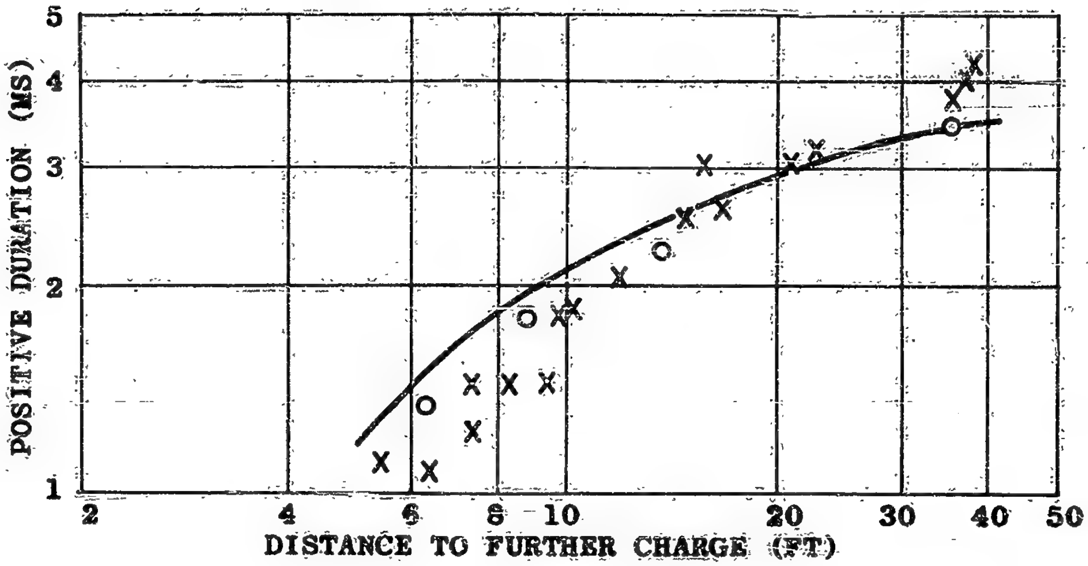


FIG. 5 DURATION OF THE POSITIVE PHASE



CURVE REPRESENTS THE ACCEPTED VALUE OF POSITIVE DURATION FOR 1 POUND OF SPHERICAL PENTOLITE

X REPRESENTS MEAN VALUE OF POSITIVE DURATION FROM 2 ONE POUND CHARGES OF PENTOLITE (AFTER SHOCKS HAVE COMBINED) PLOTTED AT THE DISTANCE OF THE FURTHER CHARGE

O EXPERIMENTAL VALUES OF POSITIVE DURATION FOR ONE POUND OF PENTOLITE (MEAN OF TWO VALUES)

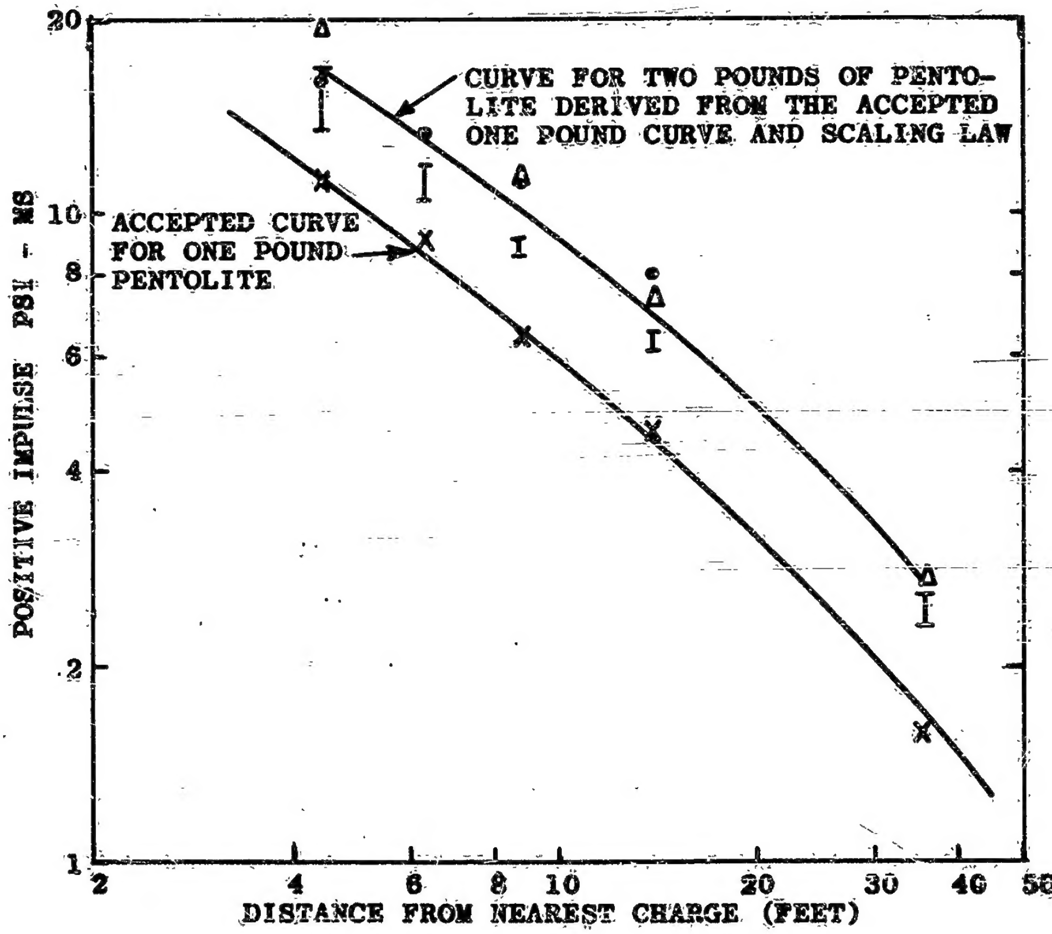
I RANGE IN WHICH THE MEAN VALUES OF POSITIVE IMPULSE FALL AFTER CATCH UP FOR 1, 2 AND 3 FOOT CHARGE SEPARATIONS

⊕ EXPERIMENTAL POSITIVE IMPULSE VALUES FROM 2 ONE POUND SPHERES OF PENTOLITE TIED TOGETHER (MEAN OF TWO VALUES)

X EXPERIMENTAL POSITIVE IMPULSE VALUES FROM A ONE POUND SPHERE OF PENTOLITE (MEAN OF TWO VALUES)

Δ MEAN VALUE OF POSITIVE IMPULSE AFTER CATCH UP FROM 2 ONE POUND SPHERES LOCATED AT THE SAME RADIAL DISTANCE AND FIRED AT DIFFERENT TIMES (O' CHARGE SEPARATION)

FIG. 6 POSITIVE IMPULSE VS DISTANCE FROM NEAREST CHARGE



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